Application of Alternative Fumigants Through Drip Irrigation Systems

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ABSTRACT

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Strawberry fields in California (9,500 ha annually) are pre-plant fumigated with methyl bromide and chloropicrin to prevent serious soil pest and disease problems. Although soil fumigation with methyl bromide has ensured stability of strawberry production, its use is being discontinued because of its effect on stratospheric ozone. The likely short-term alternatives such as 1,3-dichloropropene, chloropicrin, and metham sodium, although not ozone depleters, are potentially hazardous to the environ-

ment and humans if applied improperly. Water-soluble formulations of alternative fumigants can be applied through drip irrigation systems established to irrigate crops. In comparison to conventional shank methods of injection, application of soluble formulations through drip irrigation systems would be economical and environmentally friendly, reduce worker exposure, and allow for simultaneous or sequential application of a combination of fumigants. This paper discusses techniques developed to apply alternative fumigants through drip irrigation systems, and reviews ongoing studies to determine optimum application rates, soil conditions, plastic mulches, and amount of irrigation water used to apply these alternative fumigants.

The scheduled phase-out of methyl bromide (MeBr) has stimulated considerable research to identify alternative fumigants and to evaluate techniques to apply them for pre-plant soil fumigation. For uniform distribution of alternative fumigants, applications with irrigation water through drip irrigation systems may be a more effective method than conventional shank injection into soil in raised-bed culture. Application of some alternative fumigants with water through drip irrigation systems has been the focus of recent research to ensure a more uniform distribution of fumigants in the soil (1,9,23). Furthermore, application of soluble formulations to raised beds through drip irrigation systems can be economical and is likely to reduce emissions, worker exposure, and the amount of chemicals applied relative to conventional shank application. Although information about the application of fertilizers through the various irrigation systems is available (5), little is known about fumigant application with irrigation water. Several variables may affect the efficacy of drip fumigation in controlling soilborne pathogenic fungi, nematodes, and weeds. These include fumigant/emulsifier formulation, fumigant application rate, amount and rate of water application, irrigation uniformity, soil characteristics (soil texture, permeability, organic matter, and water content, etc.), and environmental conditions. The objectives of this review are to summarize techniques and recent developments in drip fumigation and to discuss the main criteria for successful application of emulsifiable concentrate (EC) formulations of fumigants.

Soil disinfestation for controlling soilborne plant pathogens and parasitic nematodes has relied heavily on the use of fumigants. In addition to MeBr and mixtures of MeBr and chloropicrin (Pic),

the commercially available fumigants are Pic alone, methyl isothiocyanate (MITC), and 1,3-dichloropropene (1,3-D) alone (Telone II, Dow AgroSciences) or in combination with chloropicrin (Telone C17 and Telone C35 that contain 17 and 35% chloropicrin, respectively). Other experimental alternative fumigants include propargyl bromide (PrBr) and iodomethane (methyl iodide, MeI). These fumigants are volatile organic compounds that vaporize when they are injected into the soil. Typically, MeBr is applied to soil by injection through shank-mounted tubes that are pulled through the soil either at shallow depths (20 to 30 cm) followed by covering the soil with plastic film or at deeper depths (60 to 80 cm) followed by surface soil compaction.

The primary mechanism by which shank-injected fumigants move through the soil profile after injection is vapor diffusion, and the efficiency of this movement determines soilborne pest control efficacy (14). The alternative fumigants can also be applied to soil by shank injection. However, 1,3-D, Pic, PrBr, and MITC have low vapor pressures and high boiling points relative to MeBr or MeI (Table 1). Therefore, their efficacy in the control of soilborne pests is more dependent on the method of delivery into the soil, soil type and condition, and meteorological conditions (4,16). For example, because of its low vapor pressure, metam sodium (a generator of MITC) applied by shank injection moves only a short distance from the points of injection, resulting in inadequate lateral and downward distribution for effective pathogen control (11,24). Metam sodium generally has been more effective when applied with water that distributes the fumigant in the soil (3,10,21,22,24).

Chemigation. Chemigation is the process of applying a chemical (fertilizer, pesticide, and plant growth regulator, etc.) to the soil or plant with irrigation water. Depending on the type of agricultural chemical, chemigation may be called fertigation, herbigation, insectigation, or fungigation. Use of an irrigation system may provide more uniform distribution of chemicals without causing mechanical damage to crops and compaction of the

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soil associated with other methods of chemical application. Chemigation can be a safe and effective method of treating agricultural fields provided that the injection and irrigation systems are properly designed and operated, and safety precautions are followed. The process can be economical because little extra equipment or energy is required. Fertigation is a common practice with sprinkler and micro-irrigation systems, and is occasionally done with surface irrigation. Pre-emergent herbicides and systemic insecticides are occasionally applied with irrigation water. Metam sodium, which produces the fumigant MITC, is often applied with sprinkler systems.

Drip irrigation systems are well suited for the application of some fumigants (drip fumigation) and may be advantageous for delivery of methyl bromide alternatives for soil treatment of irrigated croplands. Our research shows that EC formulations of fumigants can be applied with water through the same drip irrigation systems that are later used to irrigate the crop (1,26,27). Ongoing research is determining parameters for successful drip fumigation with several alternative fumigants for various soil types and conditions.

Drip irrigation systems. Drip irrigation of row crops has increased considerably in recent years because it can apply water precisely and uniformly to the soil, and thus reduce water loss, increase crop yields, and reduce fertilizer and cultural costs. For example, drip irrigation systems are being used in plastic-mulched, raised-bed culture by nearly all strawberry growers in California (12,17). A wide variety of drip irrigation systems are available (6). Thin-walled (0.1 to 0.2 mm) drip tubing (tape) commonly used in annual fruit and vegetable crops have emitters spaced from 10 to 60 cm apart with discharge rate ranges between 0.7 and 3.0 liter h^{-1} (at 60 to 80 kPa of water pressure). Strawberry beds are usually irrigated with one or two drip tapes (emitter spacing 20 or 30 cm) placed a few centimeters below the soil surface (28). The selection of drip tape (emitter spacing, discharge rate) and tape location depends on soil type and its infiltration rate, bed width and plant spacing, and on the crop water requirements (18).

The irrigation system is a critical part of drip fumigation because both fumigant distribution and worker safety depend on the integrity of the delivery system. The irrigation system should be carefully checked for uniform pressure and water distribution and to make sure it is free of leaks. We encourage drip fumigators to upgrade some of their field irrigation system fittings to minimize leakage. For drip irrigation systems, uniformity of water application depends on the operating pressure, emitter spacing and discharge rate, tape diameter and length, field slope (topography), manufacturing variability of the emitters, and clogging. The design of a drip irrigation system is usually based on field water distribution uniformity of at least 80% and emission uniformity along the drip tape of 90% or more. Pressure regulators and water flow meters should be used to assure proper operation of the irrigation system, especially where terrain is uneven.

It is crucial that the irrigation system components used for drip fumigation are made of materials that are chemically compatible with the applied fumigant. Polyethylene is compatible with most fumigants, but polyvinyl chloride can be exposed to high concentrations of a fumigant (1,3-D and Pic, etc.) for only short periods of time. The irrigation system and fumigant injection equipment should be monitored during any fumigant application. If water ponding or run-off occurs, the application should be discontinued immediately. After fumigant application, additional irrigation water should be applied to flush the fumigant out of the irrigation system. However, excessive flushing should be avoided because it may reduce the effectiveness of treatment or contaminate shallow groundwater.

Fumigant injection systems. Selection of an injection system for drip fumigation depends on the amount and type of fumigant, emulsifier, duration of fumigant application, water line pressure, and water flow rate. Several types of injection systems are used to deliver fertilizers and other chemicals into the irrigation water. Most of these systems, however, require tanks that are open or vented to the atmosphere. The common types of chemical injectors are mechanical pumps (positive displacement or diaphragm) and venturi systems (in-line pressure differential). These systems can be adjusted for various flow rates. With venturi injector systems (Mazzei Injector Corporation, Bakersfield, CA), a pressure-reducing valve or booster pump forces water from the main line through a restriction, creating a vacuum that withdraws the chemical from a container into the water line. Proportional feed or proportional flow systems (Hutching Company Inc., Penryn, CA) can be used to inject fumigants into the irrigation systems. These systems depend on a water flow measuring unit that sends a signal to a controller, which in turn regulates the speed of the chemical pumping mechanism. Detailed information on the various chemical injectors, safety hardware, and calibration requirements for chemigation can be found elsewhere (2,5,20,25).

We prefer to inject fumigants directly from nitrogen-pressurized cylinders. This simple method is accurate and safe. The emulsified fumigants are metered into the irrigation systems with pressure-regulators and stainless steel or Teflon needle valves and flow meters (such as those available from Key Instruments, Trevose, PA; Cole-Palmer Instrument Co., Vernon Hills, IL; or McMaster Carr Supply, Los Angeles, CA). A main advantage of this system is that it is driven by water pressure in the drip irrigation system and does not need an electrical source or battery power to operate. The portions of the injection system that come into contact with concentrated fumigants must be made with corrosion-resistant chemical-resistant parts such as stainless steel or Teflon.

The emulsified fumigant can be premixed (formulated) or field-mixed, depending on the label instructions. Preformulated EC fumigants (such as InLine, Dow AgroSciences) simplify the field injection process. Field mixing of fumigant and emulsifier during injection can reduce formulation costs, container and dispensing equipment incompatibility, container maintenance costs, and storage requirements. The system, however, must accurately regulate the emulsifier flow to ensure that the proper amount is added and adequately mixed with the fumigant prior to injection into the irrigation systems.

TABLE 1. Physico-chemical properties of various soil fumigants

Soil fumigant[a]	Water solubility at 20°C (%, wt/wt)	Vapor pressure at 20°C (mm Hg)	Boiling point (°C)	Henry's constant (K_H) (air/water)	Half-life in soil (day)
MeBr	1.34	1,420	4	0.244	22
MeI	1.40	400	42	0.210	20[b]
PrBr	1.49	72	88	0.046	5
MITC	0.76	21	119	0.011	7
1,3-D	0.22	34	104	0.056	11
Pic	0.20	18	112	0.093	1

[a] MeBr, methyl bromide; MeI, iodomethane (methyl iodide); PrBr, propargyl bromide; MITC, methyl isothiocyanate; 1,3-D, 1,3-dichloropropene; and Pic, chloropicrin.
[b] Half-life was estimated from three studies and ranged between 4 and 43 days.

The flow range of the injection system must be able to accommodate the application rates and concentrations required. Fumigants generally are injected at very low flow rates relative to the water flow rate. Fumigant concentration in the main line may vary from 300 to 2,000 mg liter^{-1}, depending on the crop, soil, fumigant type and application rate, and irrigation amount. As a rule of thumb, the fumigant injection system should be able to inject up to 0.2% of the irrigation water flow rate. Therefore, accurate calibration of injection equipment is essential for proper application. Because fumigant application through drip irrigation systems is done over 2 to 10 h, depending on the application rate and irrigation system, fumigant flow rates are often small, and small differences in the injection rate make a large difference in the total amount of fumigant applied. The fumigant should be injected into the center of the irrigation supply pipeline to improve mixing. A static mixing device (TAH Stata-Tube Mixer; TAH Industries, Inc., Robbinsville, NJ) can be installed after the point of injection to thoroughly mix fumigants with water before being distributed into the irrigation system laterals and drip tape. Another static mixing option is a filter housing containing a coarse plastic mesh to help blend the fumigant with water.

To apply a fumigant to small plots, flow rates are very low and dilution of emulsified formulation may be needed to achieve accurate application rates. Continuous mixing is required to prevent phase separation in the fumigant/emulsifier/water system, especially at low fumigant dilution. For our research, we have used an adjustable-flow positive displacement pump (Inject-O-Meter Manufacturing Company, Inc., Clovis, NM) and premixing tanks (Midwest Technologies, Inc., Springfield, IL) with excellent results. For commercial systems, premixing should be avoided due to potential safety hazards and because some fumigants hydrolyze/degrade after mixing with water if not applied immediately.

The fumigant injector must be equipped with a check valve to prevent water from flowing back into the injection system and an automatic quick-closing valve to stop fumigant injection when water flow is interrupted or the irrigation system loses pressure. The irrigation system must have check valves, a vacuum breaker, and a low-pressure drain upstream of the injection point to prevent possible contamination of the water source by fumigants from backflow (2). The irrigation line or the water pump must include a functional pressure switch that will stop the irrigation water pump or alert the applicators if the line water flow or pressure changes, indicating either interruption of the water supply or major leakage from the distribution system. The system requirements may include a functional normally closed valve located at the intake side of the injector and connected to the system interlock to terminate fumigant injection when the irrigation pump stops. Another option is a hydraulically activated, normally closed valve (Amiad Filtration Systems, Oxnard, CA) to prevent fumigant from flowing into the irrigation line if water pressure drops (Fig. 1). Alternative injection equipment may be substituted according to regulations by the U.S. Environmental Protection Agency (30). We recommend that any commercial fumigant injection system be
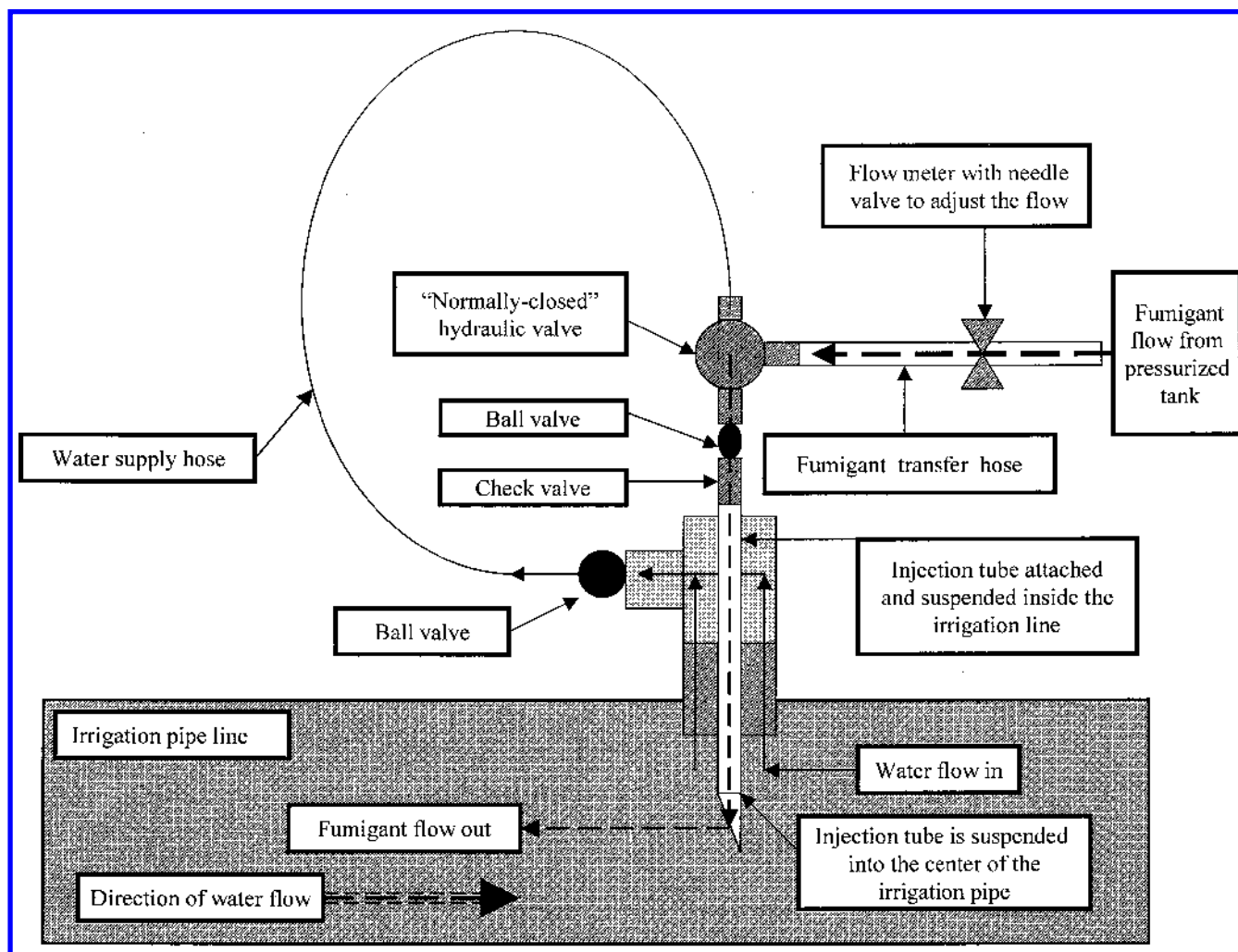

Fig. 1. Typical configuration of a fumigant injector from a pressurized tank into the main irrigation supply line. The system includes a hydraulically activated, normally closed valve to prevent fumigant from flowing into the irrigation line if water pressure drops.

a closed system to reduce worker and off-site exposures during application.

Fumigant volatilization and atmospheric emission reduction. Controlling release and off-site drift of fumigants is of particular concern to current and future use. This poses a serious concern for long-term use of alternative soil fumigants because of the lack of volatilization control. Chemical emissions from the soil during and after application may lead to atmospheric contamination and health risks, and therefore require restrictions. Although the alternative compounds currently under evaluation are not considered stratosphere ozone-depleting compounds like MeBr, the U.S. Environmental Protection Agency still may ban them if not applied safely (29). Much laboratory research on alternative fumigants has been conducted to quantitatively determine the volatility of each compound and how to improve agricultural management practices to reduce atmospheric emission of these chemicals (8,9). In controlled laboratory columns, 1,3-D emissions were detected within 7 h after fumigation and peaked within 24 h after soil injection of the fumigant (9). Generally, most volatilization occurs during the first 5 days following fumigation (15).

Standard high-density polyethylene (HDPE) film commonly used for soil fumigation is somewhat permeable to MeBr and similar soil fumigants (34). Use of alternative polyethylene-based films with much lower permeability than conventional plastic mulch may provide the means for retaining soil fumigants within the soil (7,32). These film products are called virtually impermeable films (VIF) because they are only slightly permeable to soil fumigant gases. Another benefit of VIF use is the potential for increased chemical efficacy and reduced application rates due to increased pesticide retention within the soil (33). Water seals or caps (high soil water content at the surface soil layer) can also provide an effective barrier to fumigant emissions.

Our field research on fumigant distribution in raised bed culture has shown the beneficial use of VIF to reduce atmospheric emissions. Enhanced fumigant efficacy was shown with greater concentrations of 1,3-D found in the gaseous phase of soil covered with VIF compared with HDPE mulch (Fig. 2). In a field shank application study, Nelson et al. (19) compared the atmospheric release of 1,3-D through HDPE and VIF tarped beds to beds left uncovered. They found that peak release of 1,3-D from all treatments occurred within the first 24 h after fumigant application and VIF beds had 1,3-D concentrations in soil air space twice that of polyethylene-treated beds and four times that of untarped beds.

Drip fumigation appears to be an effective method of reducing 1,3-D emissions compared with conventional shank-injected fumigation. Gan et al. (9) determined that emulsified formulations of 1,3-D resulted in the least amount of fumigant loss when compared with 1,3-D applied under HDPE tarp or when injected 20 cm deep followed by application of water to form a water seal. Recent studies (32) found that drip fumigation with 1,3-D, applied under tarp at shallow depth or without tarp at deeper depth, lead to sufficient chemical concentrations to kill nematodes equivalent to that of deep shank-injected application.

Our results demonstrated that drip fumigation under standard HDPE film led to more uniform distribution of 1,3-D in soil than shank-injected application in some sandy loam soils in California (Fig. 2). The water from drip application distributes the fumigant across the soil profile and also acts as a barrier to prevent fumigant volatilization through the soil surface and into the atmosphere. This may allow for reduced chemical application rates. Shank fumigation can lead to the rapid release of chemicals through soil cracks and channels left from the shank passing through the soil. Low soil water content in shanked fields can also lead to large soil temperature fluctuations and increased fumigant loss.

The use of VIF may further reduce emissions following drip fumigation. For example, our research showed that an emulsified fumigant formulation of 1,3-D plus 35% Pic (InLine) at 236 liters ha^{-1} in 43 mm of water resulted in higher concentrations of 1,3-D under VIF than under HDPE film (Fig. 2). Also, the concentration of 1,3-D and Pic in the soil air space of drip-fumigated beds was greater under VIF than HDPE film over a 14-day sampling period. These results indicate that reduced rates of fumigants should be effective if VIF is used in drip fumigation. For any treatment, however, the greatest concentrations of 1,3-D or Pic in the soil gas were found 24 to 36 h following application and were below the detection level 14 days following application.

Effect of water amount on fumigant distribution. Drip fumigation differs significantly from other soil fumigant application options in that it requires an understanding of the effects of initial soil water conditions and knowledge of the hydraulic characteristics of the specific soil to be treated. Estimating how far water will move in a specific soil during drip fumigation is very important because a fumigant initially moves with the water. Soil water
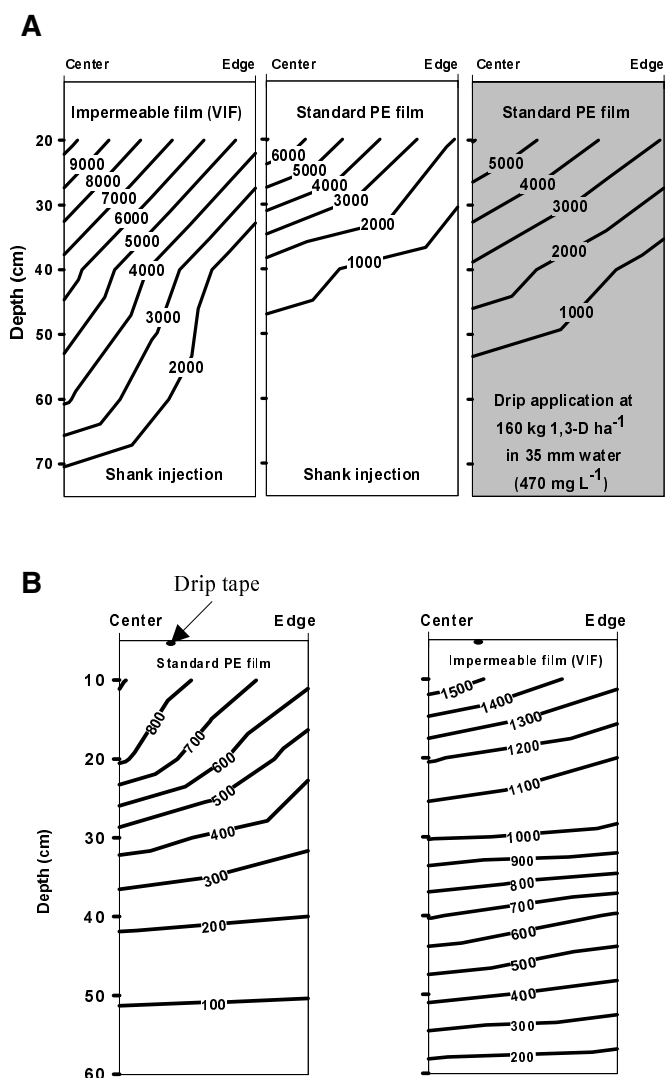

Fig. 2. **A,** The concentration of 1,3-dichloropropene (1,3-D) (microgram of 1,3-D per liter of air) in the gaseous phase of a Salinas sandy loam soil 24 h after application of Telone C35 by drip fumigation under standard polyethylene (PE) film and by bed shank injection under virtually impermeable and standard polyethylene (PE) films. **B,** The concentration of 1,3-D (microgram of 1,3-D per liter of air) in the gaseous phase of a Watsonville sandy loam soil 24 h after drip application of InLine at 236 liters ha^{-1} (58% 1,3-D) under virtually impermeable and standard PE films. The distance from the center to the edge of the bed, shown by the length of the *x* axis, is 38 cm. The shaded square shows the position of the drip tape (two tapes per bed). Lines of equal fumigant concentration were determined by gas sampling probes buried at 10, 20, 30, 40, and 60 cm at 0, 15, and 30 cm from bed center.

distribution is determined by soil properties and the manner in which water is applied. Factors affecting water distribution around the drip line include soil hydraulic properties (water holding capacity, hydraulic conductivity, and initial soil water content, etc.), water application rate, drip system configuration (emitter spacing and distance between the drip lines, etc.), and bed configuration (height and width of the bed). Water tends to move more horizontally in a dry soil than in a wet soil, and the ability of a soil to hold water decreases with increasing water content.

Several models of soil water movement (13,31) can be used to predict the soil water distribution during and after drip application. Our group is gathering information on water and fumigant distribution patterns for various soil types and under different drip tape configurations. This information will be used to optimize drip fumigation parameters and to refine models for accurate prediction of water and fumigant distribution in soil. Examples of water and fumigant distribution patterns in a Watsonville sandy loam soil before and 24 h after applying one rate of InLine (393 liters ha^{-1}) in three different amounts of irrigation water to strawberry beds (76 cm wide) through two drip tapes (each located 12 cm from the bed center) are presented in Figure 3. These results show that the concentration of 1,3-D in the soil air space was greatest with the largest amount (61 mm) of irrigation water, even though the concentration of 1,3-D in the applied water was the least (450 mg liter^{-1}). Measurement of greater concentrations of fumigants in the soil air with large volumes of water suggest that water reduces fumigant volatilization losses, possibly by reducing the total air space in soil or by forming a water seal. Our studies indicated that a minimum of 40 mm of water is needed to deliver sufficient fumigant horizontally 30 cm in a sandy loam soil (i.e., to the edge of strawberry beds). For all amounts of water used, however, the concentrations of 1,3-D or Pic were very small in the soil gas phase at depths below 60 cm.

Effect of physico-chemical properties of fumigants. For accurate prediction of fumigant distribution in soil during drip fumigation, factors such as lateral and longitudinal dispersivity (rate that the solute spreads in water through molecular diffusion and dispersion) and retardation factors or soil sorption coefficients for a specific fumigant must be known. After drip application, the behavior of fumigants is a function of their water solubility, volatility, hydrolysis and degradation rates, and their sorption to soil organic matter and clay. Several physico-chemical properties of MeBr and the other alternative fumigants are good indicators of how each chemical will behave in the soil-air-water system (Table 1).

Although fumigants are soluble in water to varying degrees, an emulsifier generally is needed in drip fumigation to ensure uniform field distribution. Therefore, the selection of an appropriate emulsifier determines the success of fumigation. Movement of an EC formulation with water depends on its physical and chemical stability and uniform dispersion of the organic liquid phase in water and the soil matrix. Several factors, including water hardness and dissolved salts, dilution rate, time, temperature, and the presence of other solvents or fumigants, may affect the stability of an EC formulation. Due to their high vapor pressure, fumigants will likely volatilize and diffuse into the soil gas after drip fumigation. Adsorption to organic matter and clay may remove a portion of fumigants from soil solution and reduce their reactivity. Addition of an emulsifier, however, will significantly change their volatility and sorption behavior in the soil solution. Field and laboratory studies are being conducted to determine the major variables that control the fate of emulsified formulations of fumigants under various soil and environmental conditions.

We compared the movement of several fumigants applied to beds of a Watsonville sandy loam soil through two drip tapes in 50 mm of irrigation water. Initially, most of the applied water was found in the bed center between the two drip tapes (Figs. 3 and 4). Redistribution of the water occurred within the first 24 h after

irrigation with a uniform distribution throughout the bed by 72 h (Fig. 4). The EC formulations of fumigants tended initially to follow water flow, with highest concentrations located at bed center. However, movement of a fumigant through the soil profile differed based on its physico-chemical properties. The physico-chemical properties of Pic are similar to those of 1,3-D (Table 1). Our studies found that Pic moved with the water flow initially, and its lateral and downward movement was similar to that of 1,3-D as shown in Figures 2 and 3. A large portion of Pic, however, remained within the upper 30 cm of the soil bed (data not shown). Also, Pic did not readily move with the total applied water as concentrations in the soil air decreased quickly, possible due to its short half-life in soil (1 day).

The physico-chemical properties of MeI are similar to those of MeBr (Table 1). MeI has a high vapor pressure (400 mm of Hg)
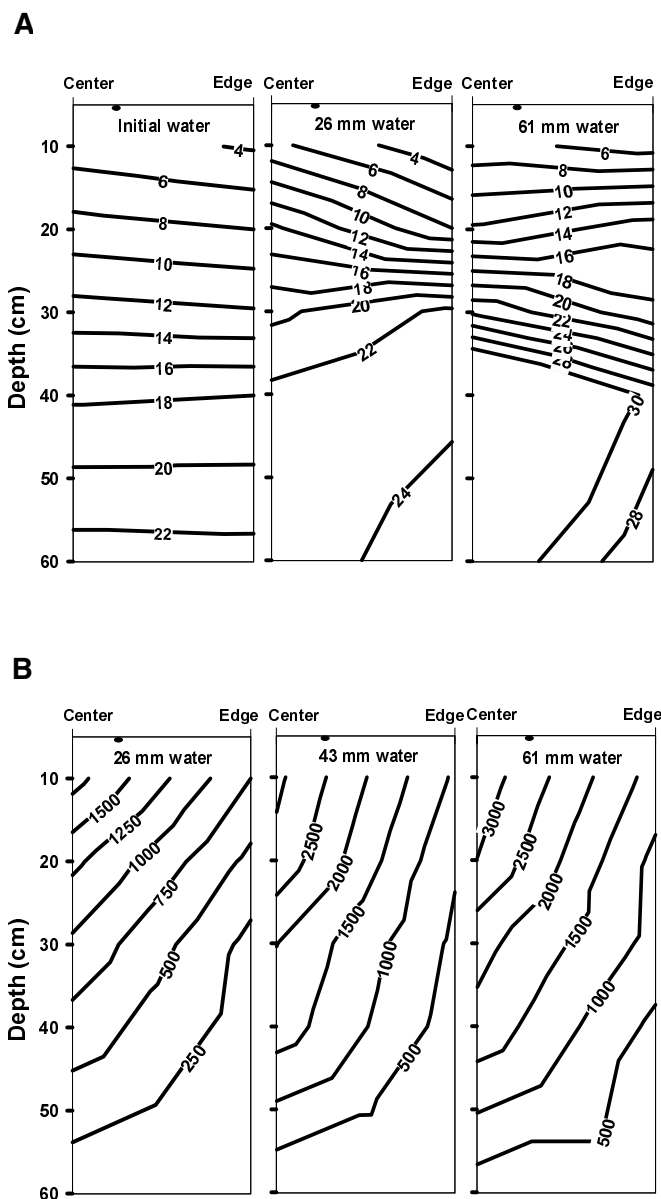
Fig. 3. **A,** Water distribution (percent soil water content by volume) in a Watsonville soil before and 24 h after applying 26 and 61 mm (26 and 61 liters of water per square meter of soil, respectively) of irrigation water through two drip tapes (4.6 liter/h per 100 m). **B,** The concentration of 1,3-dichloropropene (1,3-D) (microgram of 1,3-D per liter of air) in the gaseous phase of a Watsonville sandy loam soil 24 h after drip application of InLine at 393 liters ha^{-1} (58% 1,3-D) in three amounts of irrigation water. Soil water contents were measured periodically at 10, 20, 30, 40, and 60 cm depths at 0, 15, and 30 cm from bed center using Sentek units (EnviroScan).

and an air/water partitioning coefficient (K_H) of 0.210, indicating a very strong preference for the gas phase relative to the liquid phase. The dissipation of MeI from the water phase occurred quickly (within the first 24 h) after fumigation and its distribution in the gas phase was greatest in the upper 30 cm near the bed center. The gas moved uniformly because water and chemical were transported laterally and downward in the soil bed. The high vapor pressure of MeI caused high levels of this fumigant to move

throughout the entire bed to a sampled depth of 60 cm. Although PrBr and MeI differ in most of their physico-chemical properties (Table 1), the distribution patterns of these two fumigants in the Watsonville soil were somewhat similar (Fig. 4). The water solubility of PrBr (1.49%) is similar to that of MeI (1.40%). Therefore, both fumigants moved with water laterally and vertically in the soil bed. However, the majority of PrBr was located within the upper 30 cm of the bed and extended to the edge of the bed by 24 h after fumigation. The rapid disappearance of PrBr from the upper 30 cm of soil by 72 h after fumigation may be due to its short half-life (5 days) in soil. The inverse of the air/water coefficient ($1/K_H$) can provide an estimate of the amount of fumigant required in the water phase to produce one unit in the gas phase of a closed static system. The inverse of the K_H (i.e., water/gas) for PrBr is approximately 22, which is significantly higher than that of MeI (<5). Therefore, the distribution patterns of MeI in the soil air space are characteristic of a highly volatile compound, whereas the distribution of PrBr is more typical of a semivolatile compound.

CONCLUSION

Although the alternative fumigants can be applied to soil by shank injection, these fumigants have relatively lower vapor pressures and higher boiling points than MeBr, and their efficacy to control soil pathogens and weeds is more dependent on the application method, soil type and condition, and ambient conditions. Drip irrigation systems can serve as a vehicle to deliver water-soluble formulations of fumigants to the target soil volume and may provide a more uniform distribution of chemicals in the soil than shank injection. However, the physico-chemical properties of the applied fumigant, soil properties and condition, and the method of water application to the soil profile determine soil water distribution. Drip fumigation is still in its infancy. Further research is needed to optimize parameters for drip fumigation, including determining minimum application rates, best mulching to reduce emissions and maximize efficacy, best soil conditions, optimum water carrier amounts, and most efficacious combinations of chemicals.

Fig. 4. A, Water distribution (percent soil water content by volume) in a Watsonville sandy loam soil 6, 24, and 72 h following application of 50 mm of water (50 liters m^{-2}). **B,** Iodomethane (MeI) concentration (microgram of MeI per liter of air) in a Watsonville sandy loam soil 6, 24, and 72 h following application in 50 mm of water. **C,** Propargyl bromide (PrBr) concentration (microgram of PrBr per liter of air) in a Watsonville sandy loam soil 6, 24, and 72 h following application of 50 mm water. Methods are the same as described in Figure 3.

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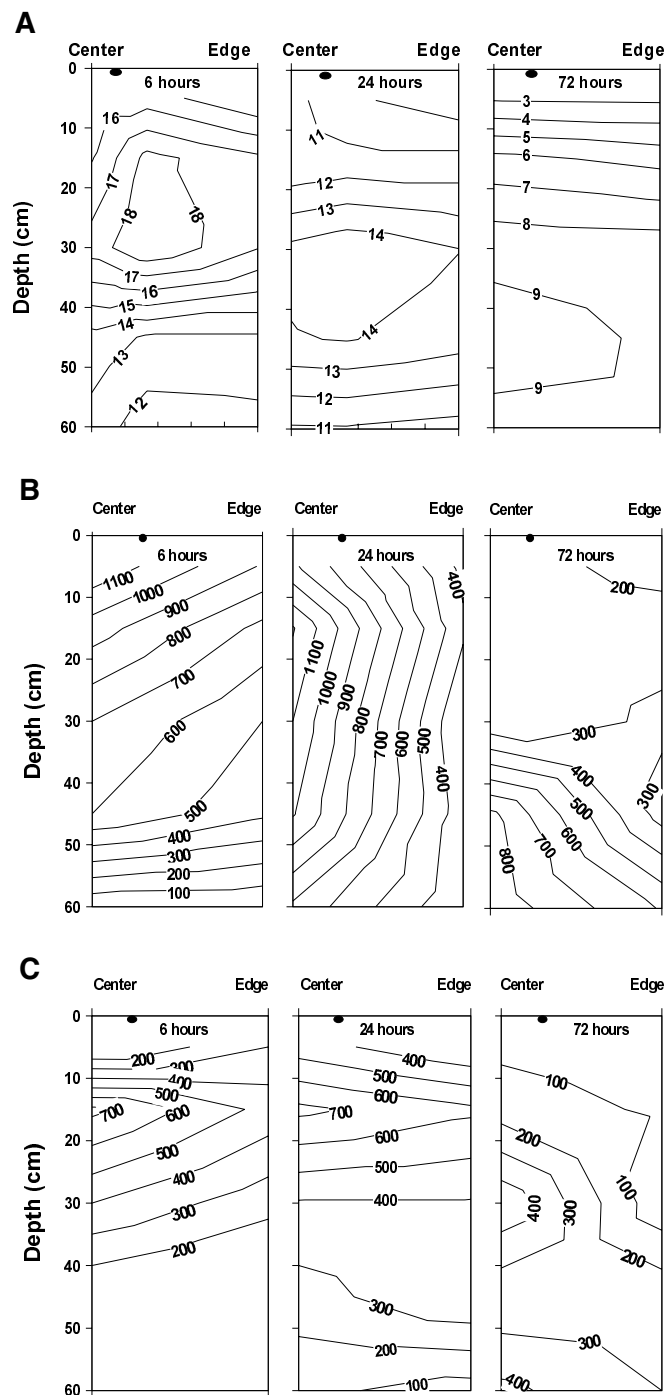
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